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ROLLING-ELEMENT FATIGUE LIVES OF AISI T-1, AISI M-42, AISI 52100, AND HALMO AT 150° F

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16. Abstract

Rolling-element fatigue tests were run with 1/2-inch- (12.7-mm-) diameter balls of AISI 52100, AISI T-1, AISI M-42, and Halmo. Tests were run in five-ball fatigue testers at 800 000 psi (5.52×10^{9} N/m^{2}) at a temperature of 150° F (340 K). Care was taken to maintain constant all variables known to affect rolling-element fatigue life. The longest lives were obtained with AISI 52100. The difference between lives of Halmo and AISI 52100 is not statistically significant. The confidence that AISI 52100 is superior in rolling-element fatigue to AISI T-1 and AISI M-42 is 98 percent and > 99 percent, respectively. A trend is indicated toward decreased rolling-element fatigue life in alloys with increased total weight percent of such elements as molybdenum, chromium, vanadium, tungsten, and cobalt. AISI T-1, Halmo, and AISI M-42 show at least a 200° F (111 K) advantage over AISI 52100 in elevated-temperature hardness retention capability.

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ROLLING-ELEMENT FATIGUE LIVES OF AISI T-1, AISI M-42, AISI 52100, AND HALMO AT 150° F

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SUMMARY

Rolling-element fatigue studies were performed with four consumable-electrode-vacuum-melted steels: AISI 52100, AISI T-1, AISI M-42, and Halmo. Groups of 1/2-inch- (12.7-mm-) diameter balls of each material were run in the five-ball fatigue tester at a maximum Hertz stress of 800 000 psi (5.52×10^{9} N/m^{2}), a contact angle of 30°, a shaft speed of 10 300 rpm, and a temperature of 150° F (340 K), and with a super-refined naphthenic mineral oil lubricant. Care was taken to maintain constant all variables known to affect rolling-element fatigue life.

The longest rolling-element fatigue lives were obtained with AISI 52100. The 10-percent lives of the other materials ranged from 7 to 78 percent that of AISI 52100. The 10-percent life of Halmo was 78 percent that of AISI 52100; the statistical significance of this difference is not great. The confidence that AISI 52100 is superior in rolling-element fatigue life to AISI T-1 and to AISI M-42 is 98 percent and greater than 99 percent, respectively. Lives of different heat-treatment lots of the same material differed by factors as great as 2.

A trend toward decreased rolling-element fatigue life with increased total weight percent of alloying elements such as molybdenum, chromium, vanadium, tungsten, and cobalt is indicated. AISI T-1, Halmo, and AISI M-42 show at least a 200° F (111 K) advantage over AISI 52100 in elevated-temperature hardness retention capability.

INTRODUCTION

AISI 52100 steel has been the most common rolling-element bearing material. Initially, this high-carbon chromium steel was produced by basic electric arc melting. Subsequently, vacuum-melting processes such as consumable-electrode vacuum melting

(CVM)(ref. 1) have improved the quality of the steel and thus the dynamic load-carrying capacity and reliability of bearings made from AISI 52100.

Because of a decrease in hardness with increasing temperature, AISI 52100 has been limited to applications where the maximum temperatures will not exceed 350° F (450 K). At about this temperature, its hardness drops below Rockwell C 58, which is considered a minimum hardness for rolling-element-bearing components (refs. 2 and 3).

For applications above 350° F (450 K), such as for advanced turbine engines, bearing alloys suitable for higher temperatures must be considered. These alloys contain elements such as molybdenum, tungsten, silicon, and vanadium to promote the retention of hardness at high temperatures. Typical of these alloys are AISI M-1, M-2, M-10, M-42, M-50, and T-1; and Halmo. Each material is a through-hardenable steel wherein the hardness is attained by heat treatment rather than by a case-hardening procedure such as carburizing. These materials are more difficult to grind and finish than AISI 52100 (ref. 2).

There have been a considerable number of studies performed to compare the rolling-element fatigue lives of various bearing materials (refs. 2, and 4 to 9). Typically, the required close controls of operating and processing variables such as material hardness, melting technique, and lubricant type and batch for a valid material comparison were not maintained in these studies. However, it is necessary to compare these various bearing materials in rolling-element fatigue tests or under closely controlled conditions in actual bearing tests. The more standard mechanical tests, such as tension-and-compression tests or rotating beam tests, cannot be used to determine rolling-element fatigue life (ref. 7).

Rolling-element fatigue tests were performed under closely controlled operating conditions on five materials (AISI 52100, AISI M-1, AISI M-2, AISI M-10, and AISI M-50). The results of these tests, reported in reference 10, indicate that AISI 52100 has the longest rolling-element life of these materials. The other materials gave lives ranging from 27 to 68 percent that of AISI 52100.

The work reported herein was conducted (1) to test the three additional materials (AISI T-1, Halmo, and AISI M-42) under closely controlled test conditions identical to those in reference 10 and (2) to compare the results with the results of the tests on AISI 52100.

These objectives were accomplished by testing groups of 1/2-inch- (12.7-mm-) diameter balls of each material in the five-ball fatigue tester. All balls for each material were made from one ingot of consumable-electrode-vacuum-melted material. Test conditions included a drive-shaft speed of 10 300 rpm, a contact angle of 30°, a maximum Hertz stress of 800 000 psi (5.52×10^{9} N/m^{2}), and a temperature of 150° F (340 K). A super-refined naphthenic mineral oil from a single lubricant batch was used as the lubricant. All fatigue testing was conducted at SKF Industries, King of Prussia, Pennsylvania, under NASA contract NAS 3-11617. All hardness testing was performed at NASA Lewis Research Center.

TEST SPECIMENS

Groups of AFBMA-grade-10 balls of 1/2-inch- (12.7-mm-) diameter were fabricated from AISI T-1, Halmo, and AISI M-42 materials. The chemical compositions of each are shown in table I. All balls of each material were made from one consumable-electrode-vacuum-melted ingot (ref. 11). The slight variation in composition from one lot to another of the same material is probably due to error in measurement. The balls were heat treated according to the schedules shown in table II. Each material was processed in three separate heat-treatment lots; each lot was given the same heat treatment. Photomicrographs of each material are shown in figures 1 to 3. For reference, photomicrographs of AISI 52100 are shown in figure 4. All three materials show typically larger carbides than does AISI 52100.

Hardness, retained austenite, and grain size of each material lot are shown in table III. ASTM cleanliness ratings are shown in table IV.

APPARATUS AND PROCEDURE

Five-Ball Fatigue Tester

The five-ball fatigue tester was used for all tests. The test assembly, shown in figure 5, consists of an upper test ball pyramided upon four lower test balls that are positioned by a separator and are free to rotate in an angular-contact raceway. System loading and drive are supplied through a vertical drive shaft. For every revolution of the drive shaft, the upper test ball receives three stress cycles. The upper test ball and raceway are analogous in operation to the inner and outer races of a bearing, respectively. The separator and the lower test balls function in a manner similar to the cage and the balls in a bearing. Lubrication is provided by a once-through, mist-type lubrication system.

Fatigue Testing

In each of these tests, all five balls were from the particular material lot being tested. From 25 to 30 five-ball tests were run for each material lot. Each test was suspended when either an upper test ball or a lower test ball failed, or when a cutoff time of 100 hours was reached.

Hardness Testing

The hardness of the materials was measured at both room and elevated temperatures using a standard hardness tester fitted with an inerted electric furnace. Hardness tests were performed using a 150-kilogram load and a Rockwell "C" diamond indentor. Ball specimens from the same heats as those fatigue tested herein were selected at random for hardness testing. Two 1/4-inch (6.4-mm) parallel flats were ground on each ball. The grinding was done at a very slow feed rate with a copious supply of coolant to prevent overheating of the test specimens.

Hardness measurements were taken immediately after an equilibrium temperature was reached before the heat input was increased for the next higher temperature. Approximately 1/2 hour elapsed before equilibrium was reached at each test temperature.

Method of Presenting Fatigue Results

The statistical methods of reference 12 for analyzing rolling-element fatigue data were used to obtain a log-log plot of the reciprocal of the probability of survival as a function of the log of upper-ball stress cycles to failure (Weibull coordinates). For convenience, the ordinate is graduated in statistical percent of specimens failed. From a plot such as this, the number of upper-ball stress cycles necessary to fail any given portion of the specimen group may be determined. For purposes of comparison, the 10-percent life on the Weibull plot was used. The 10-percent life is the number of upper-ball stress cycles at which 10-percent of the specimens can be expected to fail; this 10-percent life is equivalent to 90-percent probability of survival. The failure index indicates the number of system failures out of those tested. The five-ball system was considered failed when a fatigue spall occurred on either the upper or lower test balls. Analyses were also performed considering only upper-ball failures, with lower-ball failures being considered as suspensions.

RESULTS AND DISCUSSION

Fatigue Results

Four steels (AISI 52100, Halmo, AISI T-1, and AISI M-42) were tested in the five-ball fatigue tester. Groups of 1/2-inch- (12.7-mm-) diameter balls of each of these materials were tested at a maximum Hertz stress of 800 000 psi (5.52×10^9 N/m^2), a contact angle of 30^o, and a shaft speed of 10 300 rpm. Tests were run at a race temperature of 150° F (340 K) with a super-refined naphthenic mineral oil as the lubricant.

All balls for each material were made from one consumable-electrode-vacuum-melted ingot. Three lots of each material were separately heat treated, but one specific heat-treatment specification was used for each material.

The results of the fatigue tests with each heat-treatment lot of each material are shown in the Weibull plots of figures 6 to 9. Both upper- and lower-test-ball fatigue failures were considered in determining the five-ball system life in the Weibull analysis. The results for AISI 52100 were first reported in reference 10.

The 10-percent lives for each material lot are shown in table V. A 2-to-1 ratio in the 10-percent lives of two lots of the same material is observed with both AISI 52100 and Halmo. (It should be recalled that the only difference between lots of the same material is that they were heat treated separately.) This difference in fatigue life cannot be attributed to the slight differences in the material properties shown in tables III and IV, such as hardness, grain size, retained austenite, and cleanliness, since no trends are apparent. These material property differences may be a result of slight variations in execution of the heat treatment, or they may be scatter in the property measurements. The differences in 10-percent fatigue lives between material lots may also be normal scatter in rolling-element fatigue data. The 2-to-1 ratio in fatigue lives among the lots of the same material is not unexpected, based upon previous experience.

Also in table V are the results of analyses considering upper-ball failures as failures and lower-ball failures as suspensions. Including lower-ball failures as failures seems to yield a consistently but slightly lower life of each group. No significant difference between the two analyses is indicated.

Material Comparison

The tests with all three heat-treatment lots of each material were grouped together in order to compare the fatigue lives of the various materials. A Weibull analysis was performed on the combined results for each material. The results are shown in table VI. Ten-percent lives of the materials are shown in figure 10. A direct comparison shows that at the 10-percent-life level, the material with the longest fatigue life is AISI 52100. Halmo gave the next highest 10-percent life, which was about 78 percent that of AISI 52100. The shortest-life material was AISI M-42 which gave a 10-percent life of only 7 percent that of AISI 52100.

To determine the significance of these fatigue results, the confidence numbers shown in table VI were calculated by methods of reference 12. The AISI 52100 10-percent life was used as a reference. These confidence numbers indicate the percentage of time that the 10-percent life of a group of AISI 52100 balls will be greater than that of a group of balls made from one of the other materials.

The confidence number for Halmo is 76 percent. The difference in lives between Halmo and AISI 52100 is not statistically significant. For AISI T-1 and AISI M-42, however, the confidence that AISI 52100 is superior is 98 percent and greater than 99 percent, respectively.

AISI T-1 and AISI M-42 contain somewhat higher percentages of such alloying elements as molybdenum, chromium, vanadium, tungsten, and cobalt, which are used to give them better hot-hardness characteristics than AISI 52100. The higher percentages of alloys may also affect the materials' resistance to rolling-element fatigue. These results correlate well with results of reference 10 which show shorter lives with materials with higher alloy content.

The relative 10-percent lives of the materials reported herein and those reported in reference 10 are plotted against total weight percent of alloying elements in figure 11. These alloying elements include molybdenum, chromium, vanadium, tungsten, and cobalt. A trend exists toward decreasing rolling-element fatigue life with increasing alloy content. Individually, each element shows no consistent effect on fatigue life. The possible exception is tungsten, which is present in significant quantities in the four lowest-lived materials - AISI M-1, M-2, M-42, and T-1. The effect, therefore, seems to be a cumulative one. These alloying elements are essential for attaining the required hardness as well as for the retention of hardness at elevated temperatures. When present in higher percentages, however, they appear to be detrimental to rolling-element fatigue life.

AISI M-42, an alloy containing nominally 8 percent cobalt, resembles WB-49 (about 6 percent cobalt) in composition and microstructure. In bearing tests reported in reference 13, bearings with WB-49 races gave a 10-percent life that was only about one-third that of bearings with CVM AISI M-50 races. A heterogeneous structure with considerable carbide banding contributed to the relatively low bearing lives. The similar structure of AISI M-42 conceivably contributed to the lower lives of the AISI M-42 balls.

The analyses considering lower-ball failures as suspensions (table VI) show the same type of comparison as that previously discussed for the combined results.

The fatigue spalls on all materials were similar in appearance. Examination of the spalls revealed that they were subsurface in origin.

Hardness at Elevated Temperature

The measured hardness at elevated temperatures of each of the materials investigated herein is shown in figure 12. Hardness, as expected, decreases with increasing temperature. A commonly accepted minimum hardness at operating temperature for bearing components is Rockwell C 58. At a hardness below this value, brinelling and plastic deformation of the bearing races can be excessive during normal operation.

AISI 52100 has been considered useful to temperatures of about 350° F (450 K). However, the data presented in figure 12 would suggest that AISI 52100 steel can be functional at temperatures to nearly 400° F (478 K), except that from table II the tempering temperature was 350° F (450 K). Were the temperature to remain at 400° F (478 K) for any appreciable length of time beyond that which it took to perform the hardness measurements, a further decrease in the material hardness would be expected.

In order to obtain these hardness data, two parallel flats were ground on each ball specimen to be measured. For the initial hardness measurements presented in table III for the AISI 52100 steel, the average Rockwell C hardness is 62.3. This average (as were all those listed in table III) was taken from measurements made on 1/8-inch- (3.2-mm-) diameter flats. However, for all hardness measurements reported in figure 12, the flats were increased in diameter to 1/4 inch (6.4 mm).

Even though the grinding of the flats was done at a very slow feed rate with a copious supply of coolant, a certain amount of tempering of the AISI 52100 steel apparently occurred. As a result, the room-temperature hardness of the steel had dropped to a Rockwell C hardness of 61. It is speculated, however, that the curve for the AISI 52100 steel can be shifted up 1 Rockwell C point for comparison purposes. However, as the tempering temperature is approached, this upward shift may not be valid. For the other materials, where the tempering temperatures exceed 1000° F (811 K)(table II), such a shift may have more validity. This adjustment is justified by data from reference 10 where ball specimens of AISI M-1 steel were checked for hardness as a function of temperature. The room-temperature hardness of two specimens was Rockwell C 63 and 66. A constant difference of 3 to 4 Rockwell C points was observed between the two specimens as temperature was increased from room temperature to about 900° F (755 K).

The room-temperature hardnesses in figure 12 and table III show that AISI T-1 experienced about a 1-point decrease in hardness due to grinding. For the Halmo and AISI M-42, no significant changes in room-temperature hardness due to grinding were detected.

In order to compare the hardness retention capabilities of these materials, the data in figure 12 were adjusted to the same room-temperature hardness level, that being 62.5. These adjusted curves are shown in figure 13. AISI T-1, Halmo, and AISI M-42 show at least a 200° F (111 K) advantage over AISI 52100 in elevated-temperature hardness retention capability. These three materials show hardness retention characteristics very similar to those of AISI M-50, M-1, M-2, and M-10 as reported in reference 10.

GENERAL COMMENTS

The data presented herein and in reference 10 clearly show the superiority in rolling-element fatigue of AISI 52100 over other materials at the same hardness (Halmo, AISI T-1, AISI M-42, AISI M-1, AISI M-2, AISI M-10, and AISI M-50). The fatigue data were obtained at moderate temperatures, approximately 150° F (340 K). The choice of one of these other materials over AISI 52100 offers no advantage on the basis of rolling-element fatigue life, assuming that the hardness of AISI 52100 is approximately the same as the other materials at operating temperature. In the temperature range of 350° to 400° F (450 to 478 K), the hardness of AISI 52100 drops below the accepted minimum hardness of Rockwell C 58 for rolling-element bearings. The other materials are alloys that contain elements which allow them to retain acceptable hardness to higher temperatures. In general, as hardness of the components of a rolling-element bearing decreases, fatigue life decreases (refs. 6, 14, and 15). It is apparent then that as bearing temperatures approach 350° F (450 K) the choice of an alloy steel is advantageous.

SUMMARY OF RESULTS

Rolling-element fatigue studies were performed with four consumable-electrode-vacuum-melted steels: AISI 52100, AISI T-1, AISI M-42, and Halmo. Groups of 1/2-inch- (12.7-mm-) diameter balls of each material were run in five-ball fatigue testers at a maximum Hertz stress of 800 000 psi (5.52×10^{9} N/m^{2}), a contact angle of 30°, and a shaft speed of 10 300 rpm. The tests were run at a temperature of 150° F (340 K) with a super-refined naphthenic mineral oil lubricant. Care was taken to maintain constant all variables that are known to affect rolling-element fatigue life. The following results were obtained:

1. The longest fatigue lives were obtained with AISI 52100. The 10-percent lives of the other materials ranged from 7 to 78 percent of the 10-percent life of the AISI 52100.

2. The 10-percent fatigue life of Halmo was 78 percent that of AISI 52100. This difference is not statistically significant.

3. The confidence that AISI 52100 is superior in rolling-element fatigue life to AISI T-1 and AISI M-42 is 98 percent and greater than 99 percent, respectively.

4. A trend toward decreased rolling-element fatigue life with increased total weight percent of such alloying elements as molybdenum, chromium, vanadium, tungsten, and cobalt is indicated.

5. Lives of different heat-treatment lots of the same material differed by factors as great as 2.

6. The fatigue failures on the test balls of all four materials were similar and were subsurface in origin.

7. AISI T-1, Halmo, and AISI M-42 show at least a 200° F (111 K) advantage over AISI 52100 in elevated-temperature hardness retention capability.

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National Aeronautics and Space Administration,
Cleveland, Ohio, October 8, 1970,
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TABLE I. - CHEMICAL COMPOSITION OF TEST MATERIALS

Material	Heat-treatment lot	Chemical composition, percent (balance Fe)							
		C	Mn	Si	Cr	V	W	Mo	Co
AISI 52100	A	1.09	0.36	0.24	1.46	< 0.05	-----	< 0.05	----
	B	1.07	.36	.22	1.48	< .05	-----	< .05	----
	C	1.08	.34	.24	1.45	< .05	-----	< .05	----
Halmo	A	0.54	0.38	0.97	6.03	0.63	-----	4.93	----
	B	.57	.36	.97	5.98	.63	-----	4.82	----
	C	.57	.37	.97	5.95	.64	-----	4.96	----
AISI T-1	A	0.70	0.24	0.25	3.43	1.02	17.02	----	----
	B	.70	.25	.35	3.45	1.03	17.05	----	----
	C	.70	.22	.35	3.48	1.04	16.90	----	----
AISI M-42	A	1.13	0.20	0.10	4.02	1.09	1.51	7.88	8.40
	B	1.12	.20	.11	3.49	1.09	1.53	7.92	8.38
	C	1.12	.21	.14	3.92	1.07	1.49	7.86	8.42

TABLE II. - HEAT TREATMENT OF TEST MATERIALS

Heat treatment	AISI 52100	Halmo	AISI T-1	AISI M-42
Preheat	---------------	1450° to 1500° F (1062 to 1088 K)	1500° to 1550° F (1088 to 1118 K)	1550° to 1600° F (1118 to 1144 K)
Harden	1540° to 1560° F (1116 to 1121 K)	2050° to 2150° F (1394 to 1450 K)	2300°±20° F (1533±11 K)	2175° to 2200° F (1464 to 1477 K)
Quench	In oil at 100° to 130° F (311 to 327 K)	In oil to 150° F (339 K)	In molten salt to <1000° F (811 K)	In molten salt to 1100° to 1200° F (866 to 922 K)
Air cool	To room temperature	---------------	To < 150° F (339 K)	To < 150° F (339 K)
Deep freeze	-100° F (200 K) for 4 hr	---------------	---------------	---------------
Temper	350° F (450 K) for 6 hr	990° to 1010° F (805 to 816 K) for 2 hr	1150±20° F (894±11 K) for 2 hr	1010° to 1030° F (816 to 828 K) for 2 hr (twice)
Air cool	---------------	To room temperature	To < 150° F (339 K)	To room temperature (twice)
Deep freeze	-100° F (200 K) for 3 hr	-120° F (189 K) for 2 hr	-120° F (189 K) for 2 hr	-110° to -150° F (194 to 172 K) for 2 hr
Stabilize	350° F (450 K) for 2 hr	990° to 1010° F (805 to 816 K) for 2 hr	1150±20° F (894±11 K) for 2 hr	1150° F (894 K) for 2 hr
Air cool	To 100° F (311 K)	To room temperature	To room temperature	To room temperature
Stabilize	350° F (450 K) for 2 hr	---------------	1000° to 1025° F (811 to 825 K) for 2 hr	1010° F (816 K) for 2 hr
Air cool	To room temperature	---------------	To room temperature	To room temperature

TABLE III. - PROPERTIES OF TEST MATERIALS

Material	Heat-treatment lot	Average hardness,[a] RC number	Retained austenite, vol %	Austenitic grain size[b]
AISI 52100	A	62.5	4.90	13
	B	62.0	4.10	13
	C	62.5	.80	13
Halmo	A	60.8	0.60	8
	B	60.8	1.00	8
	C	61.1	1.70	8
AISI T-1	A	61.4	7.30	11
	B	61.4	5.20	9
	C	61.0	9.50	10
AISI M-42	A	61.8	1.00	9
	B	61.3	4.40	10
	C	61.3	4.90	8

[a]Hardness measurements made on 1/8-inch- (3.2-mm-) diameter flats.

[b]ASTM E 112-63.

TABLE IV. - MATERIAL CLEANLINESS RATINGS

Material	Heat treatment	Cleanliness rating[a]	
		Class[b]	Type
AISI 52100	A	B1	Heavy
	B	D1	Thin
	C	D1	Thin
Halmo	A	D2	Heavy
	B	D1	Heavy
	C	D2	Heavy
AISI T-1	A	B1	Heavy
	B	D1	Thin
	C	D1	Heavy
AISI M-42	A	A1	Thin
	B	D1	Heavy
	C	D1	Heavy

[a]ASTM E 45-63, method A. (Table shows predominate inclusion class and type.)

[b]Inclusion classes: A-sulfides, B-alumina, C-silicates, D-globular oxides.

TABLE V. - FATIGUE RESULTS WITH GROUPS OF 1/2-INCH- (12.7-mm-)

DIAMETER BALLS IN FIVE-BALL FATIGUE TESTER

[Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); contact angle, 30°; shaft speed, 10 300 rpm; temperature, 150° F (340 K).]

Material	Heat-treatment lot	Lower- and upper-ball failures				Upper-ball failures only			
		Life, millions of upper-ball stress cycles		Slope	Failure index[a]	Life, millions of upper-ball stress cycles		Slope	Failure index[a]
		L_{10}	L_{50}			L_{10}	L_{50}		
AISI 52100	A	18.5	114	1.04	22 out of 29	21.0	139	1.00	14 out of 29
	B	30.1	130	1.29	22 out of 29	31.5	161	1.15	15 out of 29
	C	12.9	84	1.00	19 out of 25	14.5	83	1.08	15 out of 25
Halmo	A	22.0	74	1.56	25 out of 30	24.2	80	1.58	23 out of 30
	B	12.9	57	1.26	28 out of 30	12.9	58	1.26	26 out of 30
	C	12.9	68	1.14	26 out of 30	15.9	82	1.15	22 out of 30
AISI T-1	A	6.6	50	0.92	26 out of 30	12.8	59	1.23	23 out of 30
	B	8.4	59	.97	26 out of 30	8.4	59	.97	26 out of 30
	C	8.5	74	.87	23 out of 30	19.4	149	.92	12 out of 30
AISI M-42	A	1.0	6.6	0.97	30 out of 30	1.5	9.2	1.05	21 out of 30
	B	1.7	8.9	1.12	27 out of 30	2.0	11.1	1.11	20 out of 30
	C	1.4	5.8	1.33	30 out of 30	1.6	6.6	1.30	25 out of 30

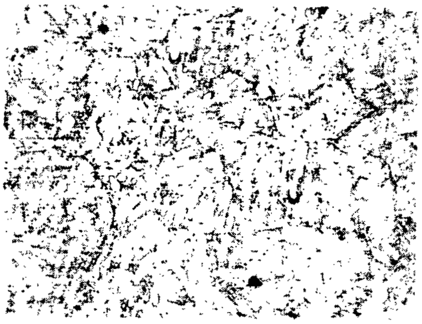
[a]Indicates number of failures out of total number of tests.

TABLE VI. - COMBINED FATIGUE RESULTS (THREE LOTS OF EACH MATERIAL COMBINED)

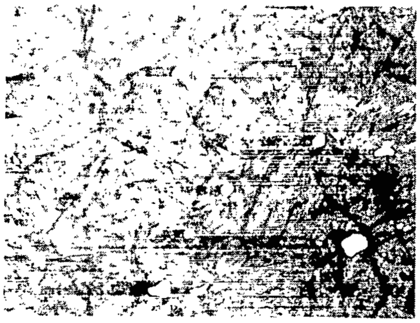
Material	Lower- and upper-ball failures						Upper-ball failures only					
	Life, millions of upper-ball stress cycles		Relative L_{10} life	Slope	Failure index[a]	Confidence number,[b] percent	Life, millions of upper-ball stress cycles		Relative L_{10} life	Slope	Failure index[a]	Confidence number,[b] percent
	L_{10}	L_{50}					L_{10}	L_{50}				
AISI 52100	21.2	109	1.0	1.15	63 out of 83	----	23.2	122	1.0	1.14	44 out of 83	----
Halmo	16.4	66	.78	1.35	79 out of 90	76	18.2	72	.78	1.37	71 out of 90	69
AISI T-1	8.6	59	.41	.98	75 out of 90	98	13.1	74	.56	1.09	61 out of 90	88
AISI M-42	1.4	7.0	.07	1.18	87 out of 90	> 99	1.8	8.8	.08	1.20	68 out of 90	> 99

[a]Indicates number of failures out of total number of tests.

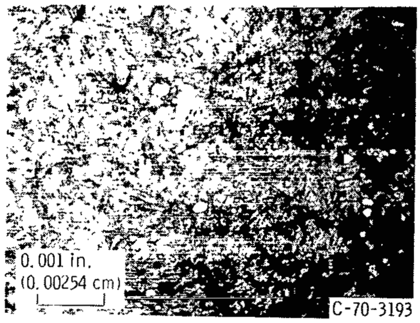
[b]Percentage of time that the 10-percent life with a group of AISI 52100 balls will be greater than that of a group of one of the other materials.



(a) Lot A.

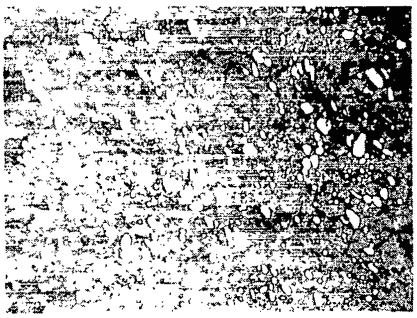


(b) Lot B.

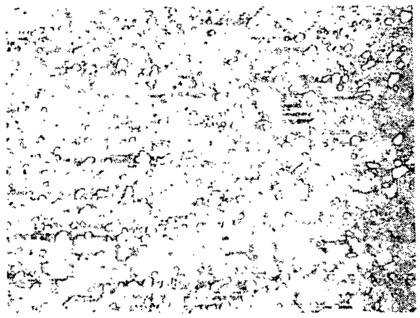


(c) Lot C.

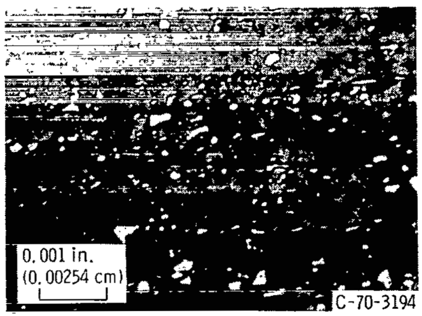
Figure 1. - Photomicrographs of the Halmo steel. Etch, 2 percent Nital.



(a) Lot A.

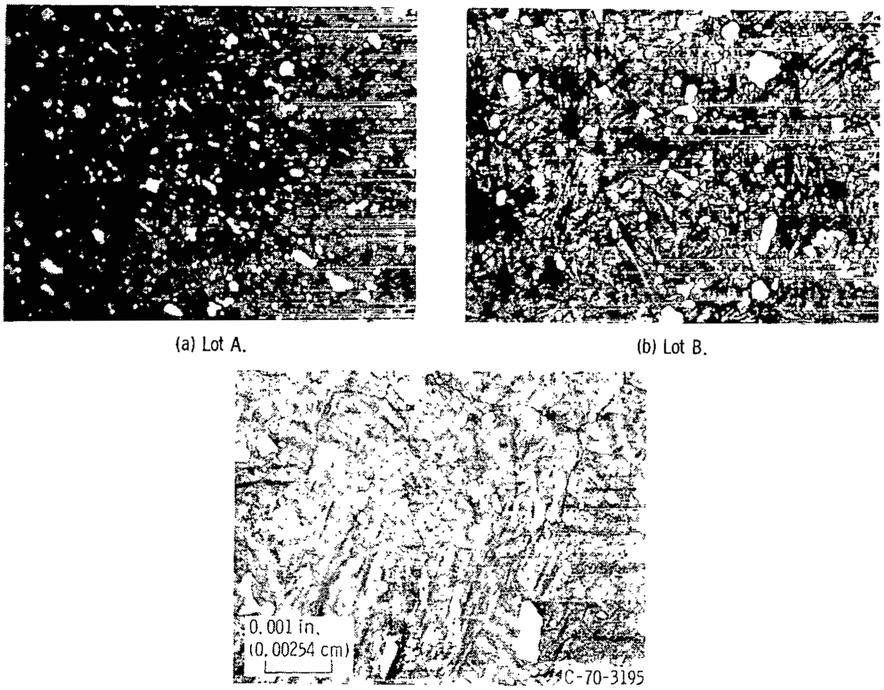


(b) Lot B.



(c) Lot C.

Figure 2. - Photomicrographs of the AISI T-1 steel. Etch, 2 percent Nital.

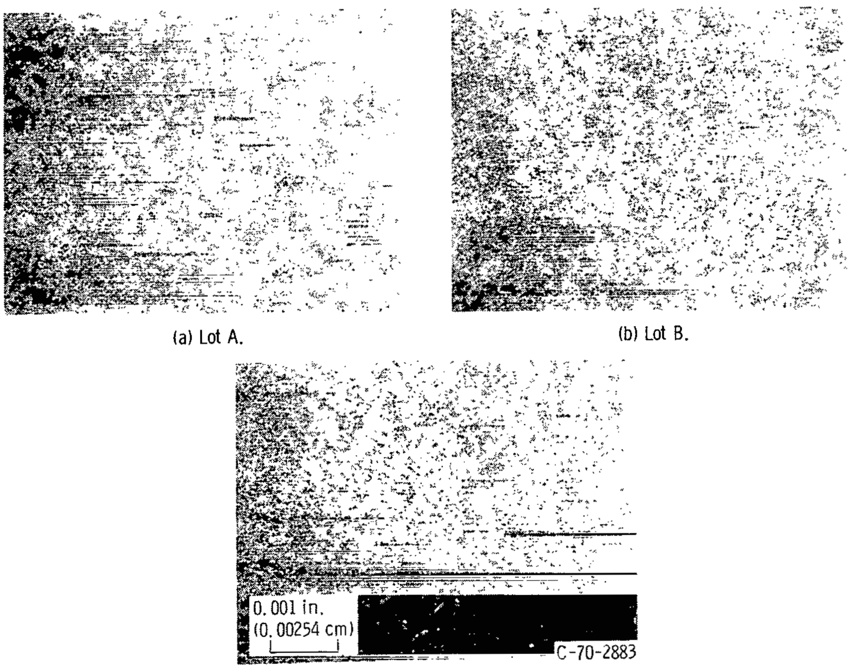


(a) Lot A.

(b) Lot B.

(c) Lot C.

Figure 3. - Photomicrographs of the AISI M-42 steel. Etch, 2 percent Nital.



(a) Lot A.

(b) Lot B.

(c) Lot C.

Figure 4. - Photomicrographs of the AISI 52100 steel. Etch, 2 percent Nital.

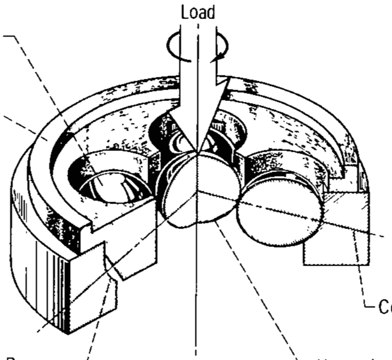
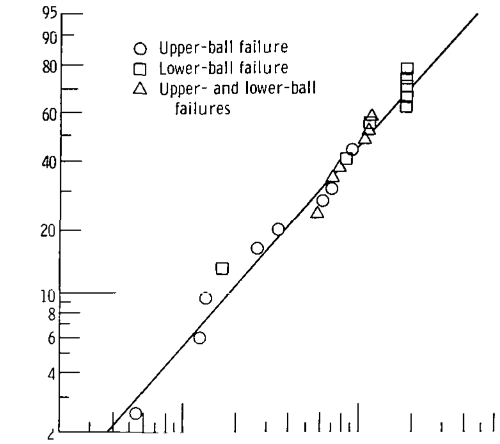
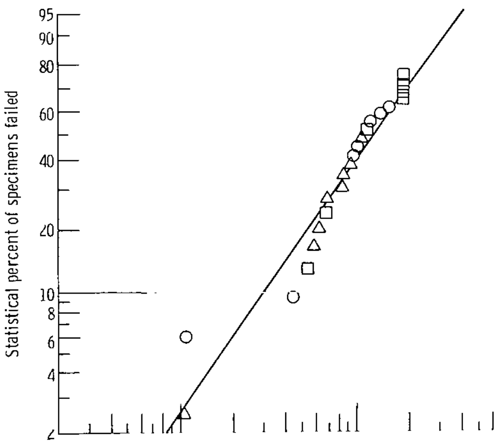


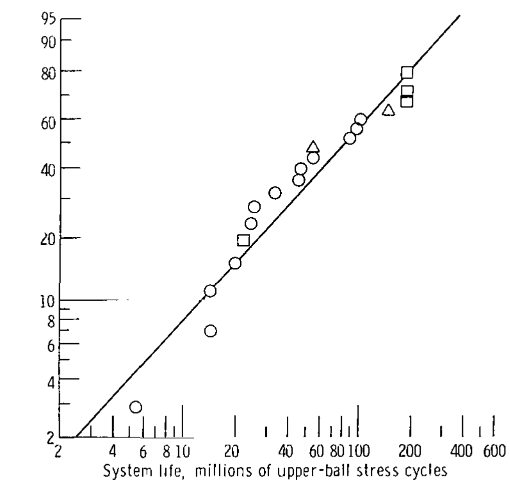
Figure 5. - Five-ball fatigue test assembly.



(a) Lot A; 22 failures out of 29 tests.

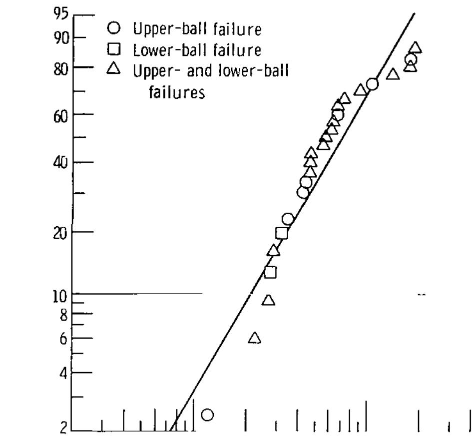


(b) Lot B; 22 failures out of 29 tests.

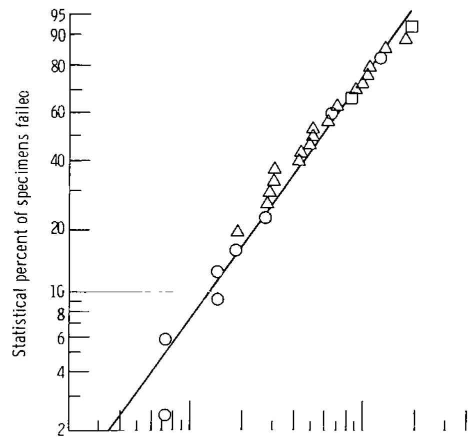


(c) Lot C; 19 failures out of 25 tests.

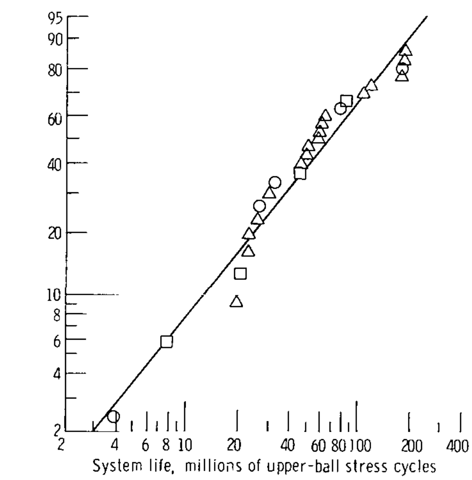
Figure 6. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter AISI 52100 consumable-electrode-vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); shaft speed, 10 300 rpm; contact angle, 30′; temperature, 150 (340 K).



(a) Lot A; 25 failures out of 30 tests.

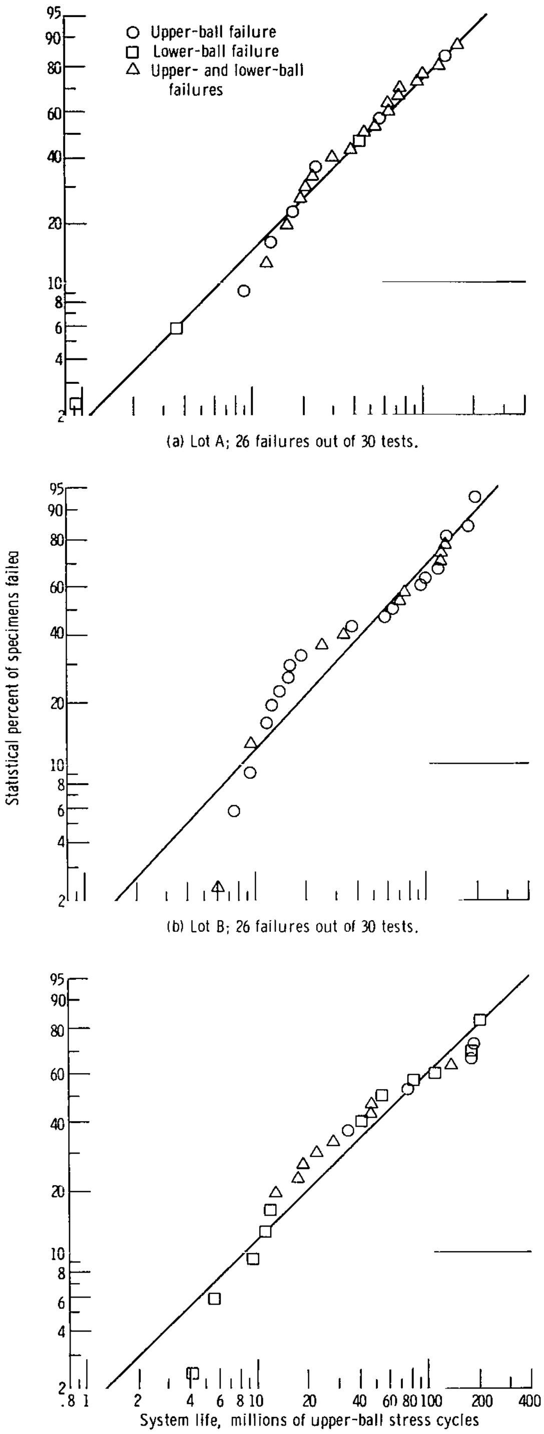


(b) Lot B; 28 failures out of 30 tests.



(c) Lot C; 26 failures out of 30 tests.

Figure 7. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter Halmo consumable-electrode-vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); shaft speed, 10 300 rpm; contact angle, 30′; temperature, 150 F (340 K).

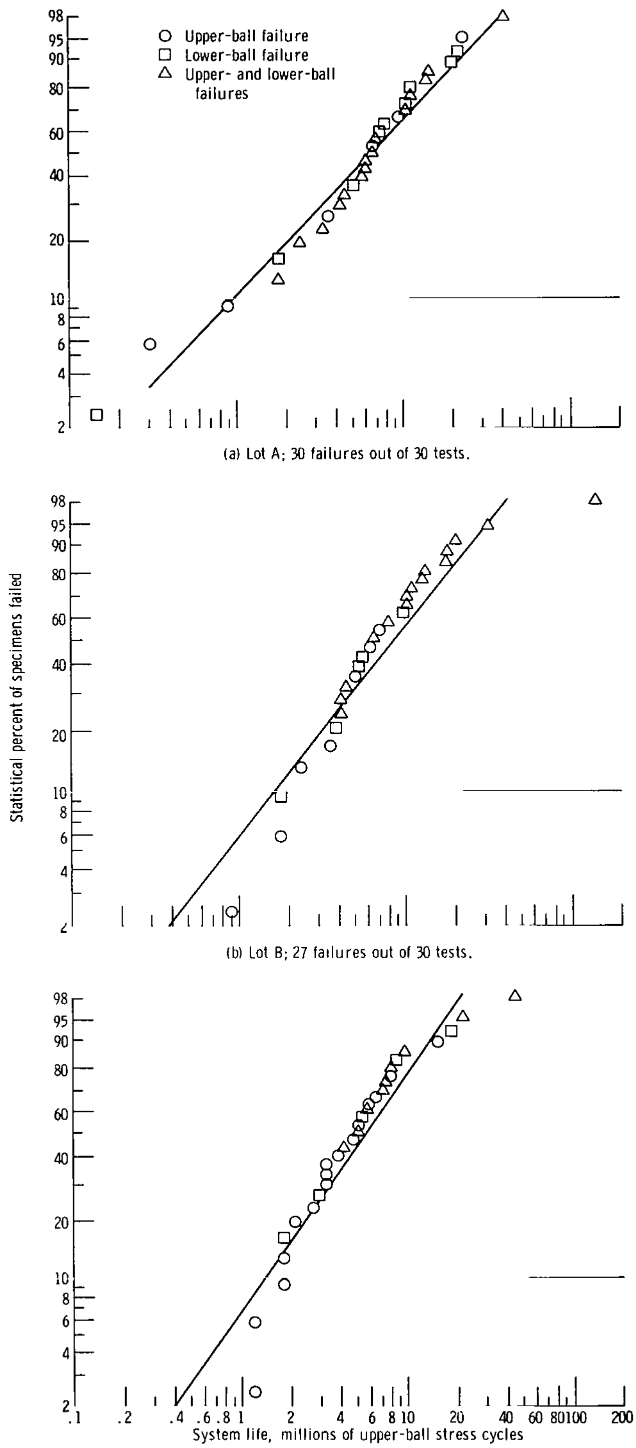


(a) Lot A; 26 failures out of 30 tests.

(b) Lot B; 26 failures out of 30 tests.

(c) Lot C; 23 failures out of 30 tests.

Figure 8. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter AISI T-1 consumable-electrode-vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); shaft speed, 10 300 rpm; contact angle, 30°; temperature, 150° (340 K).



(a) Lot A; 30 failures out of 30 tests.

(b) Lot B; 27 failures out of 30 tests.

(c) Lot C; 30 failures out of 30 tests.

Figure 9. - Rolling-element fatigue life of 1/2-inch- (12.7-mm-) diameter AISI M-42 consumable-electrode-vacuum-melted steel balls in the five-ball fatigue tester. Maximum Hertz stress, 800 000 psi (5.52×10^9 N/m^2); shaft speed, 10 300 rpm; contact angle, 30°; temperature, 150° F (340 K).

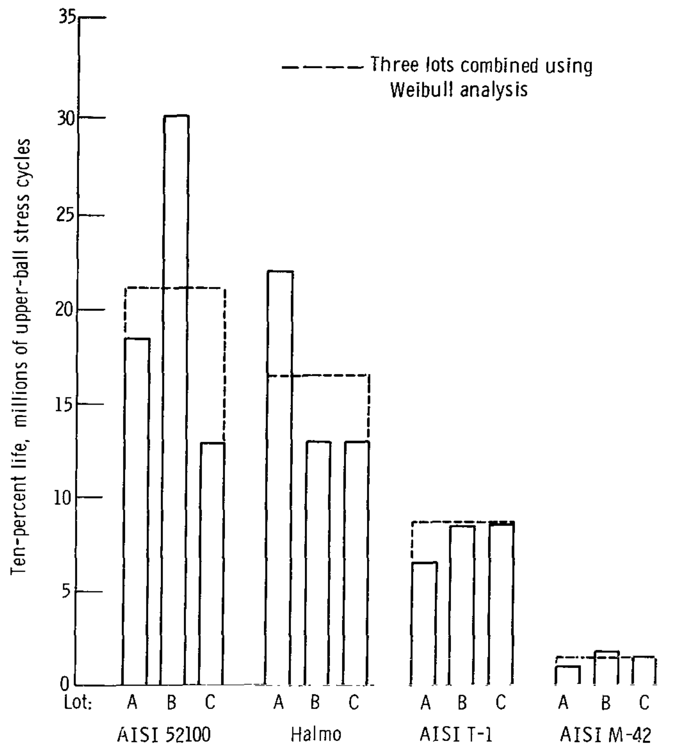


Figure 10. - Comparison of 10-percent fatigue lives of four bearing steels at 150° F (340 K).

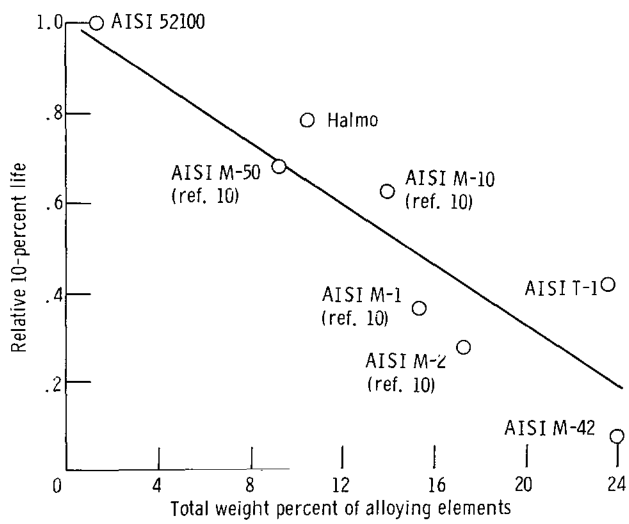


Figure 11. - Effect of total weight percent of the alloying elements tungsten, chromium, vanadium, molybdenum, and cobalt on rolling-element fatigue life.

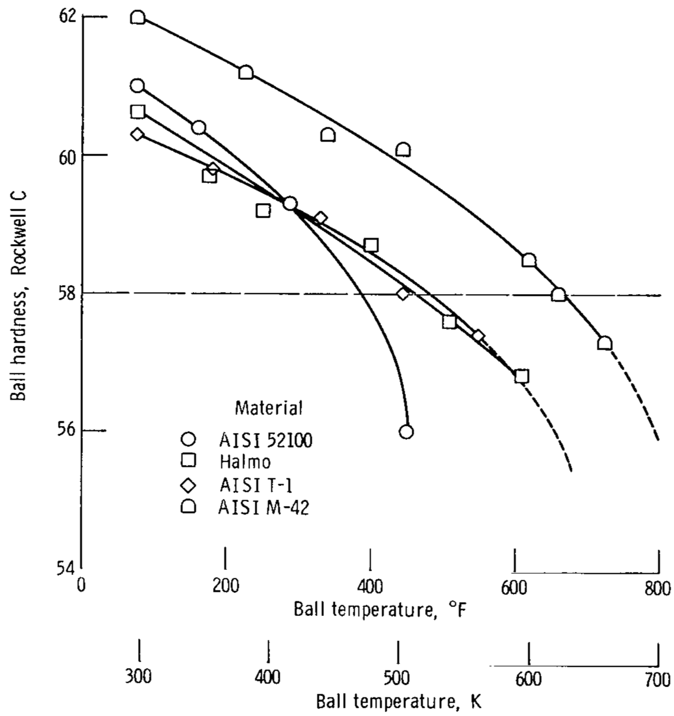


Figure 12. - Ball hardness as function of ball temperature for AISI 52100, AISI T-1, AISI M-42, and Halmo.

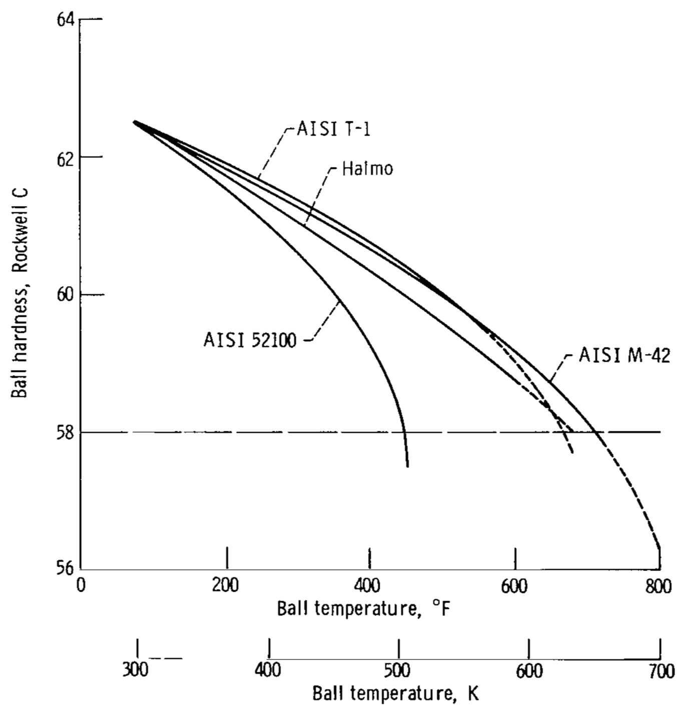


Figure 13. - Hardness of AISI 52100, AISI T-1, AISI M-42, and Halmo as function of ball temperature adjusted to a room-temperature hardness of Rockwell C 62.5.

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